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CONTRIBUTIONS FROM THE JEFFERSON PHYSICAL LABORATORY, HARVARD COLLEGE.

ON THE THERMAL CONDUCTIVITIES OF CERTAIN PIECES OF ROCK FROM THE CALUMET AND HECLA MINE.

By B. O. Peirce.

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By B. O. Peirce.

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Several years ago Dr. R. W. Willson and I presented to the Academy an account of some measurements of the conductivity for heat of several kinds of marble, and we discussed at that time * the theory of our method and described the apparatus we employed in our work. This present paper gives the results of determinations, by the same method, of the thermal conductivities of six representative slabs of rock from the Calumet and Hecla mine, very kindly lent to me by Professor Alexander Agassiz. These conductivities are interesting in view of the fact that the rate of increase of mean annual temperature with the depth seems to be very unusually small near the shaft where Dr. Agassiz's measurements were made.

Each of the slabs is a rectangular parallelopiped about four inches thick and two feet square: their average weight is a little over two hundred pounds. There are two specimens of trap, two of amygdaloid, and two of conglomerate. Each of the pieces of trap seems very homogeneous, and each piece of amygdaloid sufficiently so to make the result of each measurement an excellent determination of the mean conductivity of the slab in question: in the case of conglomerate, some variations in conductivity are, of course, to be expected in different parts of any large piece; I hope, however, that the figures given below represent with some accuracy the average conductivities of the slabs examined. The determinations involved steady work for several months.

The size of the blocks to be experimented on made some slight modi-

* These Proceedings, August, 1898. Vol. XXXIV. 1.

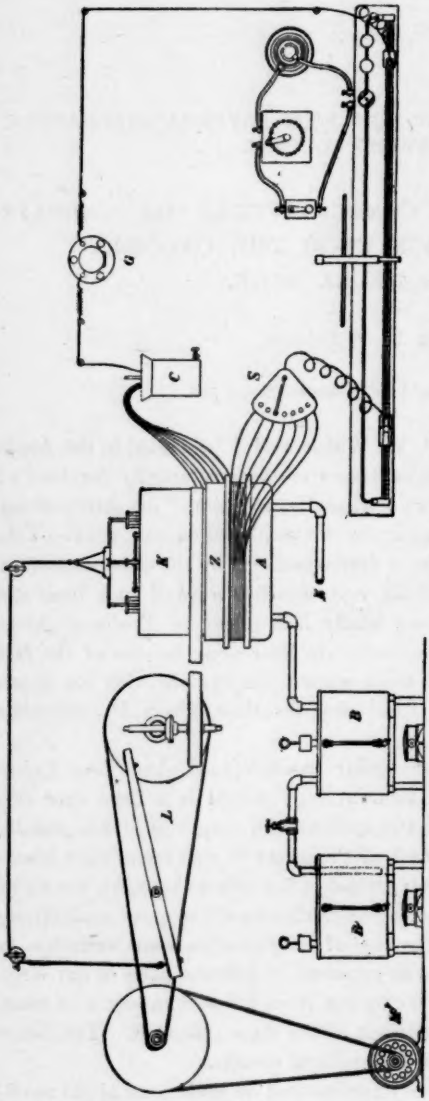

FIGURE 1.

fications necessary in the apparatus used for the work on marble, but the procedure was much the same. The square, plane-faced slab of the material to be tested, enclosed between two other thin slabs of similar material, formed a rectangular parallelopiped or prism, which was clamped and left for many hours, between the steam chest A and the ice-box Z of the apparatus, represented without any of its elaborate system of jackets, by Figure 1. The final temperatures at the centres of the faces of the slab to be tested were determined by the aid of thermal elements, and the flux of heat through a definite central portion of the colder base of the prism was measured.

The hot chamber A, which weighed about two hundred kilograms, rested in a thick jacket on a heavy table or stand made to hold it: it was connected directly with one (B) of two stout-walled copper boilers, B and B', each of which held about forty litres of water. A light cup-shaped weight inverted and laid on a large tube with smooth end which projected above the top of the boiler, acted as a sensi-

tive safety valve and prevented any appreciable rise in temperature within. B could be refilled when necessary with boiling water from B', without stopping the constant flow of steam through A by means of the siphon f which was provided with a valve. The steam, after passing through the hot chamber, was led to the outer air by a jacketed pipe h descending from the bottom of A.

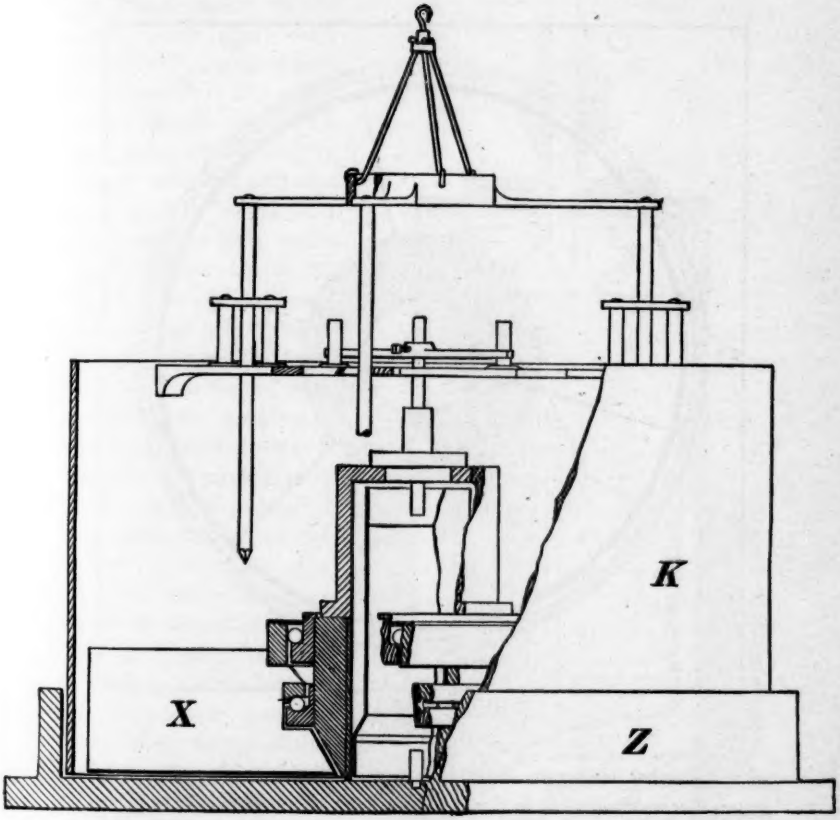

FIGURE 2.

The connections of the thermal elements were led out of the sides of the prism shut in by Z and were held between slabs of wood, which acted as a sort of guard-ring jacket to the prism, for about 40 cm. before they emerged. The platinoid or german-silver leads of these thermal

junctions within the prism were soldered together, and to a copper wire leading to the (copper) wire of a potentiometer. The copper ends of the couples led to a mercury switch by which any one of them, or any pair pitted against each other, might be quickly connected with the potentiometer. On its way from this switch to the cold junctions in *C* through the potentiometer wire the current encountered only copper. By means

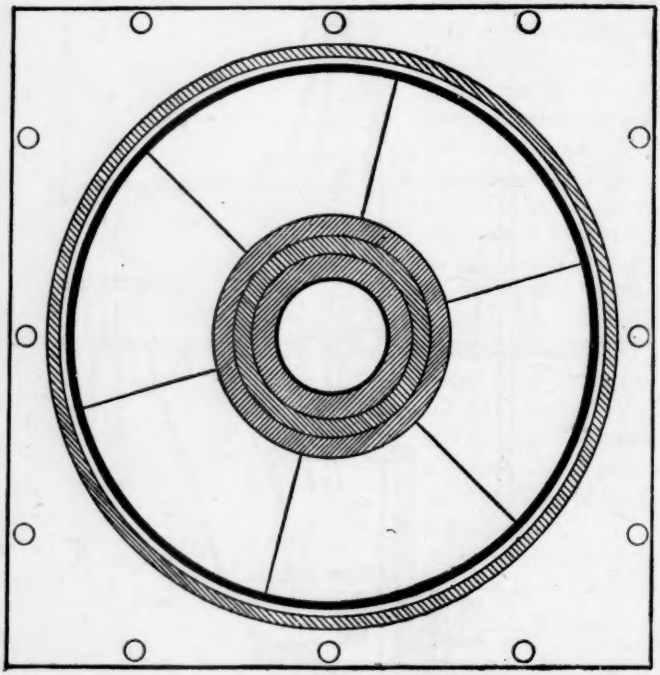

FIGURE 3.

of a somewhat elaborate standard potentiometer, not shown in the diagram, the resistance, *R*, in the potentiometer circuit could be so adjusted that a millimeter on the potentiometer wire corresponded to any desired small potential difference, such as one micro-volt or one-tenth of a micro-volt. The potentiometer wire, which was 0.25 mm. in diameter, could be changed in a few seconds for new wire if the old became dented or stretched. An iron casting *Z* (Figures 2 and 3), accurately planed below and turned true above, formed the bottom of the ice-box: it could be

bolted securely to *A* with the prism to be examined between the two. While *Z* was in the lathe, a small hole, *H*, about 3 mm. in diameter and 4 mm. deep, was drilled exactly in the centre of its upper face. Subsequently a piece of solid drawn brass tube 12.3 cm. in outside diameter and 13.5 cm. high, with carefully squared ends, was held centrally in *Z* by means of a disc turned to fit it, and a central pin inserted in *H*, and was then soldered firmly to *Z* with the help of white pitch as a flux. The walls of the pot thus formed were jacketed on the outside except for a height of about 2 mm. at the bottom (Figure 4) by an inch-thick casting of hard rubber made for the purpose in the form of a cylindrical shell. This casting, which was cut off square at the top of the pot, tapered to nothing near the bottom, but did not rest upon the floor. Upon the top of this jacket was fastened a hard-rubber cover shaped some what like a cylindrical hat. This had an opening at the top which could be closed by an accurately fitting ebonite plug. In the box, *P*, thus made, was placed a thin-walled copper ice-holder, *Q*, open at top and bottom, of the same outside diameter below as the inside of the brass pot, but some-

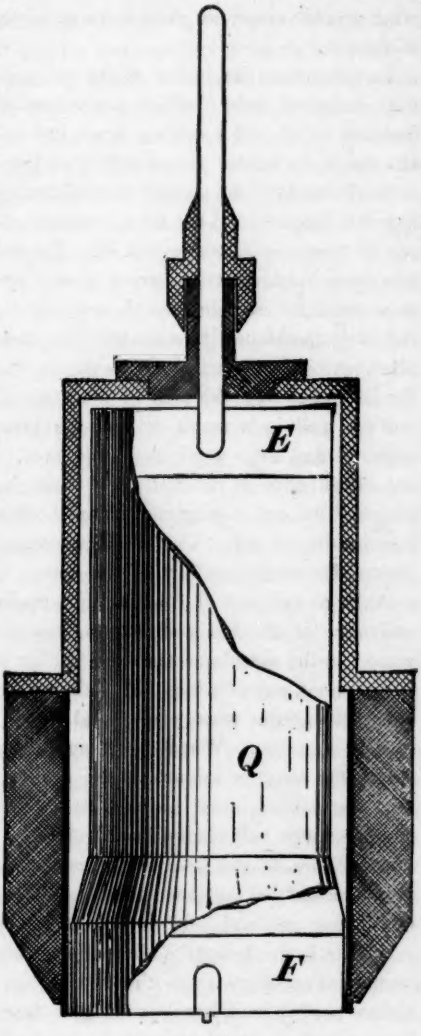

FIGURE 4.

what smaller above, so as to leave an air-space between it and the walls of the pot.

In order that the holder might be easily rotated, a pin soldered to a thin diametral web *F* which ran across the bottom of the holder was inserted in *H*, and a vertical brass rod soldered to a similar web, *E*, at the top of the holder passed through a hole in the cover of the pot which it fitted closely. An ebonite thimble fitting tightly on the rod and turning with it, permitted the slow entrance of ice-cold air into the pot without allowing any water to leak in. The rod could be clamped at pleasure to a brass yoke which is turned slowly by the electric motor. In order to prevent the introduction of heat into the pot by conduction down the rod, the exposed portion was buried in cracked ice. When the holder was filled with ice and turned by the motor, the web at the bottom compelled the ice to rub over the floor of the casting, since the holder itself had no bottom; and as a result of this, the lower surface of the ice quickly acquired and kept a mirror-like surface. The drip from the pot came out of the edge of the casting *Z* through a straight hole about 26 cm. long and 0.6 cm. in diameter drilled horizontally in the plate and ending just inside the pot. The whole apparatus was very slightly tipped to insure the steady outflow of the drip.

A large cylinder *K*, 35 cm. high, made of rolled brass 4 mm. thick and open at the top and bottom, was mounted on brass ball-bearings placed on the outside of the hard rubber jacket of the pot, *P*, by means of six vanes, one of which, *X*, is shown in Figure 2. *K* weighed about twenty kilograms when empty, and rested upon 144 brass balls each 12 mm. in diameter. When set in motion by a slight push *K* continued to rotate for about a minute before coming to rest; it was so truly hung that the outside could be used as a pulley and the whole rotated by means of the belt shown in Figure 1. The vanes reached to within about 2 mm. of the floor of the casting, and when the whole was filled with cracked ice and then rotated, the ice at the bottom which rubbed on *Z* soon got and held a very smooth surface.

A hole in the bottom of *Z* carried away the drip and prevented any accumulation of water on the floor of the ice-box. To prevent irregularities arising from honeycombing of the ice in the box, a suitably loaded brass tripod was used to pack the ice by light blows delivered at intervals of about twenty-one seconds by aid of the lever *L*. A train of wheels was necessary to reduce the speed of *K* to one revolution in twenty seconds, though only two wheels are shown in the drawing. The tripod slid in guides which revolved with *K*, and a swivel at the top prevented the cord from twisting.

The rotation of K and of the inside ice-holder, Q, which is connected with K at the top by means of a yoke, were matters of much importance. The continual rubbing of the ice over the flat surface of the casting seems to be necessary if the upper face of the prism is to be kept at a uniform constant temperature for hours. The heat produced in rotating Q slowly was so little as to be quite negligible. The ice in K was piled up so as to cover P completely, and I was unable to detect any difference between the temperatures within and without P by fine, properly protected thermal junctions introduced for the purpose. If while K revolved, Q was kept still, the amount of ice melted in Q became irregular, though the whole amount of drip in two or three hours was not very different from the amount of steady drip in an equal time when Q was rotating. Only selected lumps of ice were put into Q. The ice to be used was first broken up into pieces weighing something like fifteen grams each, by means of an ice-cracking machine, and these pieces were then put into ice-water so that their sharp edges might become slightly rounded. They were then drained and dropped into Q. In this way a slight amount of water attached to the ice was introduced, but with the method employed, the error due to this cause appeared to be of slight importance. In some experiments the ice to be used was carefully dried in cold blotting-paper, but this precaution did not seem to be necessary if the use of small bits of ice with sharp edges was avoided. Q's capacity was about two thousand cubic centimeters. After Q had been freshly filled in the course of any experiment while K was rotating, no record was kept for some time, perhaps fifteen minutes, of the amount of drip. Before the expiration of this interval the extra water introduced into Q with the ice had drained off, and the indications had become steady. The drip tube always contained a few drops of water, but this amount remained sensibly constant during the progress of an experiment. The drip was collected in a graduated vessel and the approximate amount was noted from time to time to see whether the flow was steady. The whole was then more accurately determined by weighing, at longer intervals. The regularity of drip seemed to be a far more sensitive test of the approximate attainment of the final state of the body experimented on and its surroundings than was a sensibly constant temperature gradient on the axis. In most experiments with the apparatus a sufficiently steady state was attained in about seven hours from the beginning of the heating. Z and K together weighed when filled with ice about three hundred kilograms, and many hundreds of pounds of cracked ice were needed for a single day's experiment. The area a of the bottom of the small ice-pot

was assumed to be 126.70 sq. cm.: this includes a slight correction for the thickness of the brass walls. The latent heat h of melting ice was assumed to be 79.25.

If, then,

r = rate of melting of ice in the pot, in grams per second,
t = temperature of difference between the faces of the slab,
d = thickness of the slab,
k = mean thermal conductivity of the slab,

$$k = \frac{r \cdot d \cdot h}{t \cdot a}.$$

TABLE I.

Material.	Weight of the slab in kilograms.	Thickness of the slab in centimeters.	Density.	Temperature of the warm face of the slab.	Temperature of the cool face of the slab.	Rate of melting of ice in the pot in grams per second.	Thermal conductivity of the specimen.
Trap	97.53	8.90	2.90	83.6	23.3	0.0340	0.0031
Trap	104.80	9.70	2.82	83.7	22.1	0.0365	0.0036
Amygdaloid .	98.45	9.68	2.67	82.7	15.2	0.0385	0.0035
Amygdaloid .	95.26	9.30	2.71	83.3	22.1	0.0358	0.0034
Conglomerate	78.02	9.25	2.55	82.1	23.3	0.0480	0.0047
Conglomerate	97.50	9.85	2.64	81.1	24.7	0.0476	0.0052

Table I gives some of the data of my final determinations. It would have been easy to give the value of k with greater apparent accuracy, but, in view of the lack of homogeneity in some of the slabs, this would have been misleading. The trustworthiness of results obtained with the apparatus described above is discussed in these Proceedings for August, 1898.

Table II shows the results of other determinations of the thermal conductivities of different specimens of rock. Many of these, as will be seen, were made by Messrs. Herschel, Lebour, and Dunn for the British Association for the Advancement of Science. The names of the dif-

TABLE II.

Substances.	Observers.	Conductivities.
Fire brick	B. A. Committee	0.0017
Fine red brick	"	0.0015
Chalk	"	0.0020 to 0.0033
Tough dry clay	"	0.0022
Devonshire clay slate	"	0.0027
Whinstone trap rock	"	0.0028 to 0.0048
Caen stone	"	0.0043
Cornish red serpentine	"	0.0044
English marbles and limestones	"	0.0047 to 0.0056
Granite	"	0.0053
Sandstone and hard dry grit	"	0.0055
English plate glass	"	0.0023
American plate glass	Peirce and Willson	0.0026 to 0.0028
Carrara white marble	"	0.0051
American and Italian colored marbles	"	0.0062 to 0.0076
"Sugar-white marble"	Despretz	0.0077
"Fine-grained gray marble"	"	0.0097
Calton Hill trap (damp)	Kelvin	0.0042
Craigleith Quarry sandstone (damp)	"	0.0107
Greenwich Park gravel (damp)	Everett	0.0125
Sandy loam	Neumann	0.0136
Serpentine	"	0.0059

ferent substances are of course rather indefinite. My own experience shows that even thick sheets of fine plate glass bought at different times of the same maker may have conductivities which differ from each other by as much as eight per cent; while the conductivities of slabs of dry

white marble from different quarries may differ as much as thirty per cent. In the table I have, in two or three cases, taken the average of nearly agreeing results.

It is evident that the conductivities of the specimens of dry rock which I have examined are relatively rather low.

The Jefferson Physical Laboratory,
April, 1903.